ORGANIC MATERIAL IN THE INTERSTELLAR MEDIUM

YVONNE PENDLETON

NASA Ames Research Center, Space Science Division,
Moffett Field, CA 94035, USA

Abstract. Spectra of objects which lie along several lines of sight through the diffuse interstellar medium (ISM) all contain an absorption feature near 3.4 μm (2950 cm^{-1}) which has been attributed to saturated aliphatic hydrocarbons on interstellar grains. The similarity of the absorption bands near 3.4 μm along different lines of sight reveals that the carrier of this band lies in the diffuse dust. A remarkable similarity between the spectrum of the diffuse dust and an organic extract from the Murchison meteorite suggests that some of the interstellar organic material may be preserved in primitive solar system bodies. The recent discovery of the 3.4 μm absorption feature in other galaxies has led to comparisons between the extragalactic, galactic, and solar system organics. The comparisons show strong similarities in position peaks and profile structure between the three spectra. However, the absence, in our own galaxy, of the aliphatic hydrocarbon signature in the spectra of dense cloud objects is puzzling in the light of the widespread distribution of the aliphatic material throughout the diffuse medium and the short time scales thought to govern the transition of that material back into dense molecular clouds. The connection between the diffuse ISM dust and solar system objects is made more difficult to understand if the aliphatics are truly absent in the dense cloud phase where proto-solar nebulae must form. In an effort to further investigate the 3.4 μm absorption feature in the diffuse ISM, comparisons of the diffuse medium dust to several materials which have been proposed as "fits" to the 3.4 μm feature are presented. The optical depth/extinction τ/A_V ratio for the 3.4 μm (2950 cm^{-1}) band is higher toward the galactic center than toward sources which sample the interstellar medium in the local neighborhood. A similar trend has been observed previously for silicates, indicating that the two materials may be simultaneously enhanced in the galactic center. Such a trend is consistent with the presence of grains composed of silicate cores and organic refractory mantles.

1. Introduction

Fundamental to the study of the cosmic dust connection, and perhaps to the origin of life, are comparative studies between the organic material found in the interstellar medium (ISM) and that incorporated in the most primitive solar system bodies. Infrared observational and laboratory studies of the interstellar medium have shown that aliphatic hydrocarbon grains in the diffuse interstellar medium are responsible for the observed absorption features near 3.4 μm (Allen and Wickramasinghe, 1980; Adamson et al., 1990; Sandford et al., 1991; Pendleton et al., 1994).

Similar and/or related signatures of organic material have been found in comets, asteroids, and meteorites. Furthermore, comparisons between the aliphatic hydrocarbon absorption bands in the diffuse ISM and the Murchison meteorite have a striking similarity which suggests that a closer and more detailed investigation is merited. It is possible that some of the organic matter seen in the primitive solar system bodies originated in the interstellar medium. If the material in present day comets and meteorites is interstellar, then similar interstellar organic matter was available to the early solar nebula.

Studies of the organic component of interstellar dust have recently extended beyond our galaxy to nearby embedded Seyfert galaxies. The 3.4 μm absorption feature (in the rest frame) has recently been detected in several external galaxies, including NGC 1068 and IRAS 08572 +3915. These results indicate the widespread availability of organic material for incorporation into planetary systems, some of which are probably forming around sun-like stars.

However, the noted absence of the aliphatic hydrocarbon signature in dense cloud spectra of our galaxy (Smith et al., 1993) presents a curious situation. Since proto-solar nebulae form around stars which are themselves born in the dense molecular clouds, it is surprising that the carbonaceous meteorites look similar to the diffuse dust rather than the dense cloud dust. Clearly much more work has to be done to ascertain the evolution of the organic component of interstellar dust between the diffuse and dense cloud regimes.

Another recent finding has shown that the A_V/τ ratio for the 2950 cm^{-1} (3.4 μm) feature is lower toward the galactic center than toward sources in the local solar neighborhood ($\sim$ 150 for the galactic center sources versus $\sim$ 250 for the local ISM sources), as discussed in Sandford et al. (1995). A similar trend has been observed previously for silicates in the diffuse medium (Roche and Aitken, 1984, 1985), suggesting that the silicate and carbonaceous materials in the diffuse ISM may be physically correlated. Similar correlations between the 3.4 and 9.7 μm features have not been found, thus far, in the studies of other galaxies, but that work is in a preliminary stage at this time (Wright, private communication).

2. IR Spectroscopy and the interstellar medium

Infrared spectroscopy is fundamental to studies of the composition of interstellar dust, particularly the organic component, since all of the fundamental vibrations of biologically interesting molecules occur in the infrared (2–20 μm) region. With the exception of graphite, all of the interstellar dust components thought to be present in the interstellar medium have been proposed on the basis of IR spectroscopic observations (Tielens and Allamandola, 1987). Compositionally, about half of the volume of interstellar dust is comprised of some type of silicate material. The remaining half consists of a carbonaceous component that includes such materials as polycyclic aromatic hydrocarbons (PAHs), graphite, amorphous carbon, and refractory grain mantles. The organic component resides in the refractory grain mantle component of the dust.

A possible scenario for the evolution of interstellar dust, first proposed years ago by Greenberg and co-workers, can be given as follows: silicate dust forms in the outflows and ejecta of evolved stars during mass loss episodes, as well as in proto-planetary nebulae, novae, and supernovae. In this manner, the dust is returned to the diffuse interstellar medium, where it is later incorporated into the dense cloud medium (perhaps swept up by a shock wave into a condensed region that eventually collapses in on itself to start the star formation process). While in the protected environment of the dense cloud, icy mantles accrete and simple molecules form on the grains. Ultraviolet radiation (UV) from the embedded protostars and the ambient UV field (and other energy sources) acts upon the ice-mantled grains and complex chemistry may occur, leading to the formation of a complex organic grain mantle (Greenberg, 1978, 1982). Star formation in molecular clouds has been shown to be a rather inefficient process, therefore, some of the dust grains go into making new stars while others are returned to the diffuse ISM. Due to the harsh environment of the interstellar radiation field, icy mantles do not survive, and a complex organic grain mantle is left behind when the volatile material evaporates. Early studies of a line of sight toward the heavily obscured galactic center revealed the presence of a strong absorption feature near 3.4 μm which can be attributed to the C-H stretch in aliphatic hydrocarbons (Allen and Wickramasinghe, 1980; Butchart et al., 1986). Observations along other lines of sight have now shown that this feature arises from diffuse interstellar material, as opposed to material local to the galactic center (Adamson et al., 1990; Sandford et al., 1991; Pendleton et al., 1994). Fig. 1 demonstrates that the C-H feature (near 3.4 μm) toward various sources in the galactic center appears quite similar, while the O-H feature (near 3.0 μm) varies from source to source. The O-H is thought to be local to the galactic center, and is therefore not associated with the diffuse ISM (McFadzean et al., 1990). The absence of the 3.0 μm feature along lines of sight where the 3.4 μm feature is seen (Sandford et al., 1991; Pendleton et al., 1994) is consistent with this explanation for the galactic center objects and with that given

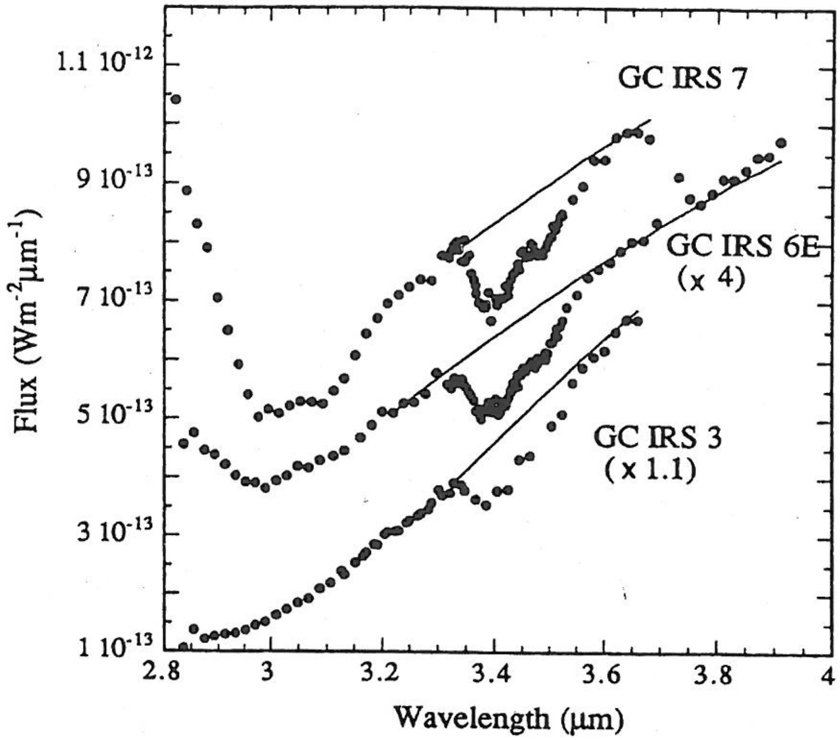

Figure 1. Flux spectra of galactic center sources IRS 7, IRS 6, and IRS 3, obtained at the NASA IRTF using the CGAS 32 channel linear array (2.7 arcsec aperture). The low resolution data ($\lambda/\delta\lambda$ = 160–210 over the 2.80–3.61 μm range) provided wavelength coverage of 0.018 μm per detector. The high resolution data ($\lambda/\delta\lambda$ = 790–880 over the 3.25–3.55 μm range) provided wavelength coverage of 0.004 μm per detector and are superposed on the low resolution data. The baselines from which optical depth plots were made are shown by the thin lines across the absorption features.

by Greenberg (1973) for the lack of a strong 3.0 μm absorption band towards the luminous supergiant, VI Cygni 12. In this early work, Greenberg stated that the more volatile ice component was absent from the spectrum while the more refractory component remained.

The positions of the 2955 cm^{-1} (3.38 μm) and 2925 cm^{-1} (3.42 μm) sub-features are characteristic of the symmetric C-H stretching frequencies of -CH_3 (methyl) and -CH_2- (methylene) groups in saturated aliphatic hydrocarbons, and the band at 2870 cm^{-1} is characteristic of the asymmetric C-H stretching vibrations of these same functional groups when perturbed by other chemical groups. The carbonaceous material in the diffuse ISM has an average -CH_2-/-CH_3 ratio of 2.0–2.5 and likely contains moderate length aliphatic chains, such as -CH_2-CH_2-CH_3 and -CH_2-CH_2-CH_2-CH_3, associated with electronegative chemical groups, i.e., moieties like -OH, -C=N, and aromatics (Sandford et al., 1991; Pendleton et al., 1994).

Improvements in detector technology have made it possible to probe the ISM in nearby galaxies for spectral information in the near-infrared region. The discovery of the 3.4 μm absorption feature in NGC 1068 (Bridger et al., 1993) has led to

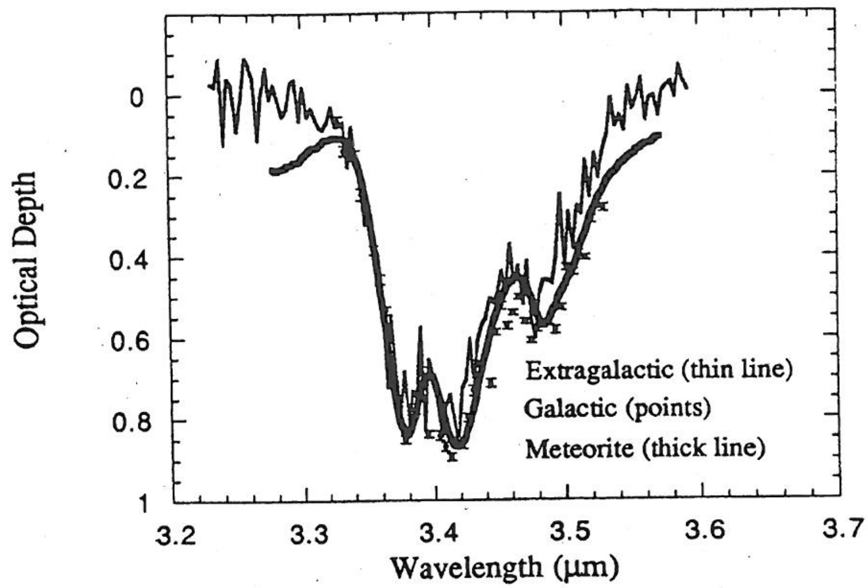

Figure 2. The 3.4 μm absorption feature observed in the extragalactic spectrum of IRAS 08572 +3915 (Wright et al., 1995; UKIRT data) (thin line), galactic center IRS 6E (Pendleton et al., 1994; NASA IRTF data) (solid points), and the spectrum of the hydrocarbons in Murchison meteorite (DeVries et al., 1993) (thick line). The spectrum of IRAS 08572 +3915 has been corrected for redshift (z=0.058) and the galactic center and meteoritic spectra have been normalized to the extragalactic spectrum at 2925 cm^{-1}.

the survey of additional galaxies in an effort to understand the correlation of this feature with other spectral components. The strongest 3.4 μm absorption feature observed so far has been found in the IRAS galaxy IRAS 08572 +3915 (Wright et al., 1995). The similarity between the extragalactic, galactic, and solar system organic material can be seen in Fig. 2, which is a comparison between the 3.4 μm absorption feature seen in IRAS 08572 +3915 located at a redshift of $z = 0.058$ (Wright et al., 1995), in our galaxy toward galactic center object IRS 6E (Pendleton et al., 1994) and in the organic acid residue from the Murchison meteorite (DeVries et al., 1993). The extragalactic spectrum has been corrected for redshift, revealing the similar wavelength peaks and profiles of the hydrocarbon bands. In this comparison, the galactic center spectrum and the meteoritic spectrum have been normalized to that of the extragalactic spectrum at 2925 cm^{-1}. The extragalactic signature is 3–4 times stronger than that seen in our own galaxy, making it possible to derive detailed profile information from this very strong source. Such a strong spectral signature suggests that we may be able to learn about portions of the spectrum that we cannot study from the ground when investigating dust in our own galaxy by looking towards redshifted extragalactic sources such as IRAS 08572 +3915.

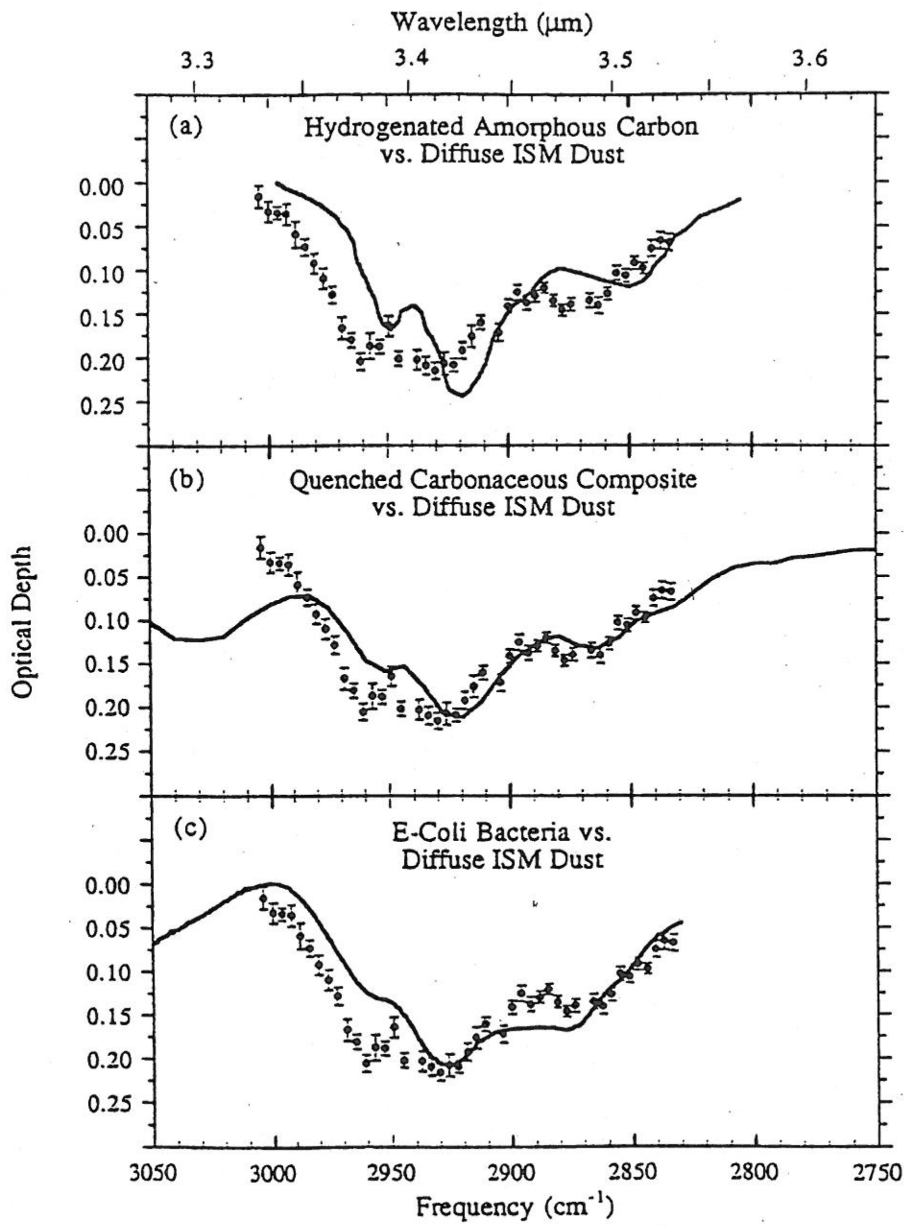

Figure 3. A comparison of the optical depth spectrum of galactic center source IRS 6E (solid points) to (a) the optical depth spectrum of a room temperature hydrogenated amorphous carbon (HAC) taken from Borghesi et al. (1987; solid line), (b) the optical depth spectrum of a room temperature filmy quenched carbonaceous composite (QCC) taken from Sakata and Wada (1989; solid line), and (c) the optical depth spectrum of E. Coli suspended in a KBr pellet. Figure taken from Pendleton et al. (1994).

3. Laboratory analogues

Additional understanding of the composition of the carbonaceous carrier in the diffuse ISM can be gained by comparing the interstellar C-H stretching feature with the features produced by other organic materials. Several materials have been suggested as candidate carriers of interstellar carbon. These include: (i) organic grain mantles consisting of a complex molecular mixture formed by irradiation of

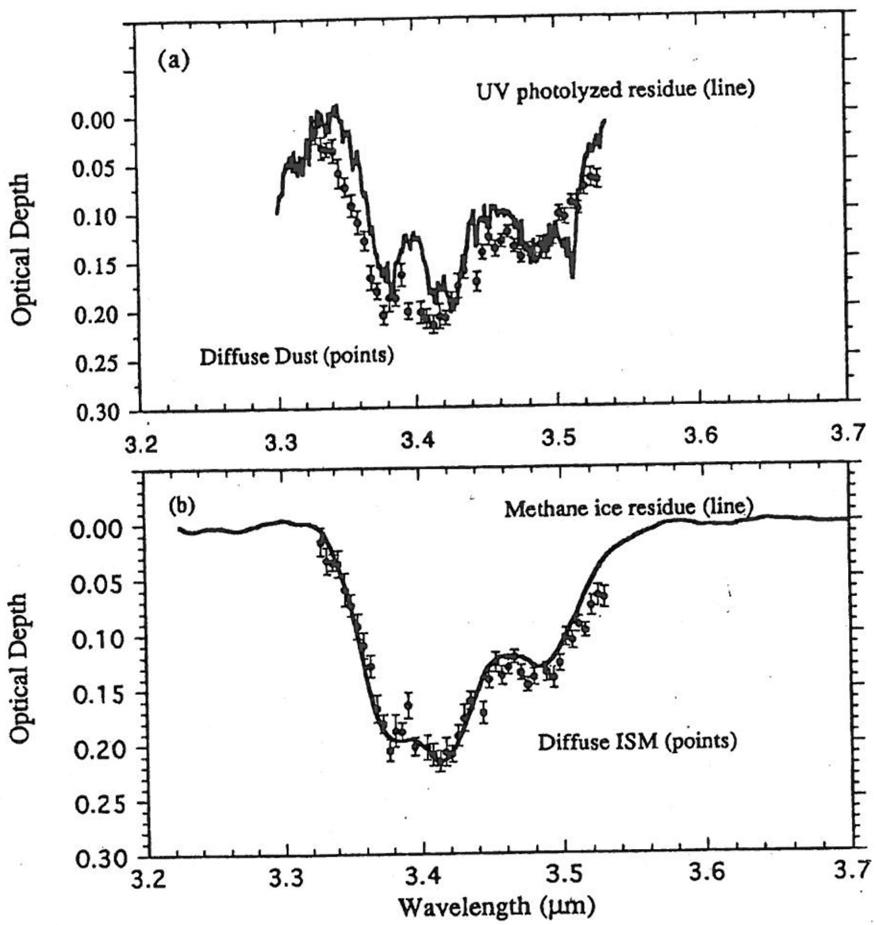

Figure 4. A comparison of the optical depth spectrum of galactic center source IRS 6E (solid points) to (a) the spectrum of a laboratory residue produced by the UV irradiation of a 10 K H_2O:CH_3OH:NH_3:CO:C_3H_8 = 10:5:1:1:1 interstellar ice analog followed by warm up to 200 K (solid line) (laboratory data from Sandford et al., 1991) and (b) the spectrum of a laboratory residue produced by irradiating frozen (10 K) methane ice with a 180 eV/C-atom dose of 75 keV protons (solid line) (laboratory data from Baratta and Strazzulla, 1990).

ices (cf. Greenberg, 1978; d'Hendecourt et al., 1985; Schutte, 1988; Sandford et al., 1991; Khare et al., 1993; Baratta and Strazzulla, 1990; Sandford et al., 1991), (ii) hydrogenated amorphous carbons (HACs) having various degrees of hydrogenation (cf. Jones et al., 1987; Borghesi et al., 1987), (iii) quenched carbonaceous composite (QCC), a material produced by quenching the plasma of methane gas (cf. Sakata and Wada, 1989), and (iv) some less plausible organic materials, such as micro-organisms (Hoyle et al., 1982). Fig. 3, taken from Pendleton et al. (1994), compares the spectrum towards galactic center source IRS 6E to three materials which have been proposed as matches to the 3.4 μm band: HAC, QCC, and E. Coli.

Laboratory experiments based on astrophysically relevant conditions are promising because a match with such materials may reveal the importance of various processes thought to occur in the development of the organic material in dense molecular clouds. Fig. 4 is a comparison of two important processes in dense molecular clouds: UV photolysis and ion bombardment. In the first case, shown in Fig. 4a, laboratory experiments were conducted by exposing simple ice mixtures typical of those thought to be present in dense molecular clouds to UV radiation. Upon heating to 200 K, after the volatiles have left, the IR spectrum of the residue from the irradiated ice mixtures provides a good match to the spectrum of diffuse ISM. Improved matches are found through repeated processing of the residue material (Greenberg, private communication). This is consistent with a scenario in which icy mantles form on grains in the dense cloud medium, are processed by ultraviolet radiation from the young stars, and are subsequently returned to the diffuse medium where the volatile material evaporates and the organic residue remains. Further processing occurs in the diffuse ISM, but eventually some of the diffuse medium dust should be reincorporated into a dense cloud where the cycle continues. However, the substructure of the 3.4 μm hydrocarbon absorption bands observed in the diffuse medium is not seen in the dense cloud medium (Smith et al., 1993). This is a problem that must be given some attention if we are to have confidence in our understanding of the evolutionary cycle of the organic component of interstellar dust.

Fig. 4b presents another astrophysically relevant process for dense molecular clouds, that of ion bombardment. The initial material used in the ion bombardment experiment represented in Fig. 4b was pure methane (Baratta and Strazzulla, 1990). Mixtures of interstellar ice analogues are underway (Strazzulla, private communication) so that we may soon be abe to tell whether it is the process or the initial material that has resulted in the improved match to the diffuse ISM which can be seen in Fig. 4b. All of the laboratory analogues, except the ion-bombarded methane, have a deficiency in the CH_3 band when compared to the ISM.

Comparison of the diffuse interstellar C-H band profiles with the spectra of laboratory samples of candidate analog materials all show general similarities to the interstellar C-H stretching feature. This is undoubtedly because all of these materials contain significant aliphatic -CH_2- and -CH_3 fractions. Comparisons with our best astronomical data show that the available spectra of many of these materials fail to fit the interstellar feature in all details, suggesting that they do not yet contain the exact mixture of molecular components present in the carbonaceous fraction of the dust in the diffuse ISM. This stresses the need for both additional high resolution, high signal-to-noise astronomical data over a wide wavelength range and additional laboratory data from a variety of materials spanning a greater composition range. To date, the best fit to the interstellar C-H stretching feature were provided by the spectrum of a carbonaceous fraction of the primitive carbonaceous chondrite Murchison (Pendleton et al., 1994). Although it does not prove it, this suggests that the carbonaceous component of dust in the diffuse ISM and the meteoritic material may be closely related and that the carbonaceous fraction of primitive meteorites may represent the best analog material presently available for the organic fraction of the dust in the diffuse ISM. As discussed in detail in Sandford et al. (1995), there is a difference between the local diffuse ISM and the galactic center A_V/τ_{CH} ratio of about a factor of 2, the same factor observed for silicates in the diffuse ISM by Roche and Aitken (1984). This implies that the grains responsible for the diffuse medium aliphatics C-H and silicate Si-O stretching bands are different from those responsible for the observed visual extinction (or at least they are not solely responsible for the visual extinction). It also suggests that the distribution of this C-H carrier is not uniform throughout the Galaxy, but may instead increase in density toward the center of the Galaxy. The matching behavior of the C-H and Si-O stretching bands suggests that these two components may be coupled, perhaps in the form of silicate core, organic mantle grains, an idea first proposed by J.M. Greenberg several years ago.

4. Summary

The carrier of the 3.4 μm band resides in the diffuse interstellar medium, as evidenced by the presence of the absorption feature along many lines of sight toward a variety of background sources. Higher resolution, higher signal-to-noise data has provided a new C-H stretching bands. Due to the higher quality data, materials that were previously suggested as fits to the 3.4 micron feature have not proven to be well matched to the diffuse medium dust. Laboratory experiments which simulate conditions occurring in dense molecular clouds are able to produce organic residues which better fit the observations. However, nature seems to have provided the best match thus far in the form of the carbonaceous meteorite. New observations of nearby galaxies have revealed the 3.4 μm absorption feature which is very similar in profile to that observed in our own galaxy. The connection between the extragalactic, galactic, and solar system organics is not clear though. Despite the difficulties of retaining a pristine interstellar signature in the parent body of the meteorite while undergoing substantial processing in the early solar system, one must also explain why the aliphatic hydrocarbon signature seen in the diffuse dust does not appear in the spectra of dense molecular cloud objects, since proto-solar nebulae must form in those environments. Nonetheless, the similarity of the features is striking and further observational and laboratory work is merited as we continue to probe this cosmic dust connection.

Acknowledgments

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